



Atmospheric and  
Environmental Research, Inc.

## **Two-Dimensional Transport Studies for the Composition and Structure of the Io Plasma Torus**

**ATMOSPHERIC AND ENVIRONMENTAL RESEARCH, INC.  
LEXINGTON, MASSACHUSETTS**

**July 25, 2003**

**Two-Dimensional Transport Studies for the  
Composition and Structure of the Io Plasma Torus**

William H. Smyth

Atmospheric and Environmental Research, Inc.  
131 Hartwell Avenue  
Lexington, MA 02421-3126

Report for the Period of  
March 19, 2003 to June 18, 2003

## I. Introduction

The overall objective of this project is to investigate the roles of local and spatially extended plasma sources created by Io, plasma torus chemistry, and plasma convective and diffusive transport in producing the long-lived  $S^+$ ,  $S^{++}$  and  $O^+$  radial “ribbon” structures of the plasma torus, their System III longitude and local-time asymmetries, their energy sources and their possible time variability. To accomplish this objective, two-dimensional [radial (L) and System III longitude] plasma transport equations for the flux-tube plasma content and energy content will be solved that include the convective motions for both the east-west electric field and corotational velocity-lag profile near Io’s orbit, radial diffusion, and the spacetime dependent flux-tube production and loss created by both neutral-plasma and plasma-ion reaction chemistry in the plasma torus. For neutral-plasma chemistry, the project will for the first time undertake the calculation of realistic three-dimensional, spatially-extended, and time-varying contributions to the flux-tube ion-production and loss that are produced by Io’s corona and extended neutral clouds. The unknown two-dimensional spatial nature of diffusion in the plasma transport will be isolated and better defined in the investigation by the collective consideration of the foregoing different physical processes. For energy transport, the energy flow from hot pickup ions (and a new electron source) to thermal ions and electrons will be included in investigating the System III longitude and local-time temperature asymmetries in the plasma torus. The research is central to the scope of the NASA Sun-Earth Connection Roadmap in Quest II Campaign 4 “Comparative Planetary Space Environments” by addressing key questions for understanding the magnetosphere of planets with high rotation rates and large internal plasma sources and, in addition, is of considerable importance to the NASA Solar System Exploration Science Theme. In this regard, Jupiter is the most extreme example with its rapid rotation and with its inner Galilean satellite Io providing the dominant plasma source for the magnetosphere. The research work is furthermore highly relevant to the scientific goals and the ongoing interpretation of data for the Jupiter system acquired by a host of ground-based facilities, the Hubble Space Telescope,

**Table 1. Three-Year Research Plan**

<b><u>Investigation</u></b>	<b><u>Year 1</u></b>	<b><u>Year 2</u></b>	<b><u>Year 3</u></b>
Step 1: Calculations for Iogenic plasma sources & lifetimes	Calculate Outer Source ion/energy productions, ion loss lifetimes, and explore Inner Sources.	Complete Outer Source calculations; continue to explore impact of molecular sources and sinks for the plasma torus chemistry.	
Step 2: Transport studies for $N_i L^2$	Add corotational-lag convection to transport equations; perform exploratory calculations.	Undertake major transport calculations for the spatial structure of the torus for an Inner Source and also Outer Source atomic sources and important molecular contributions; publish results.	
Step 3: Transport studies for $\mathcal{E}_i$ and $N_i L^2$	--	Initiate energy transport studies; explore power of Outer Source and Inner Source and torus System III longitude and local-time asymmetries.	

the Voyager, Ulysses, and ongoing Galileo missions, and by the Cassini mission in its recent Jupiter flyby. The three-year research plan is summarized in Table 1.

## II. Summary of Work Performed in the Second Quarterly Period

In the second quarterly period, research efforts have been focused upon reviewing and assessing the neutral-plasma processes and the plasma-plasma processes that are important in determining the production and loss rates for the primary heavy ion species  $S^+$ ,  $S^{++}$ ,  $S^{+++}$ ,  $O^+$ , and  $O^{++}$  in the plasma torus and in acquiring new and updating old cross sections for the important processes. Also, the addition of suitable production and loss output arrays for these species are being added as necessary in the Io neutral cloud models for O, S, SO, and  $SO_2$ .

### 2.1 Chemistry in the Io Plasma Torus

An updated list of the chemical reactions for the production and loss of ion species in the plasma torus is summarized in Table 2. The set of 45 reactions is divided into six different categories, which collectively contains 33 neutral-plasma reactions and 12 plasma-plasma reactions. Electron impact processes contribute to 18 of the reactions: 5 atomic ionization reactions, 9 molecular ionization/dissociation reactions, and 4 recombination reactions. Ion processes contribute to the remaining 27 reactions: 14 atom-ion charge exchange reactions, 10 molecule-ion charge exchange reactions, and 3 ion-ion charge exchange reactions. In our previous exploratory two-dimensional [radial (L) and System III longitude] plasma transport calculations for  $S^+$  and  $S^{++}$ , torus chemistry was limited to only the six red reactions for S to specify the primary production rate of  $S^+$  and the one green reaction for  $S^+$  to specify the primary loss rate of  $S^+$  and the primary production rate of  $S^{++}$ . The situation for the plasma transport of  $S^+$  and  $S^{++}$  is clearly much more complex than this earlier treatment since both additional production and loss contributions are also provided by the reactions involving O, SO, and  $SO_2$ . This same situation also exists for plasma transport calculations of  $O^+$  and  $O^{++}$ , which have not yet been initiated but are to be undertaken at a later date in this project.

Table 2. Chemistry In the Io Plasma Torus

<b><u>Atomic Ionization Reactions</u></b>		
k1	$e + S \rightarrow S^+ + 2e$	
k2	$e + S^+ \rightarrow S^{++} + 2e$	
k3	$e + S^{++} \rightarrow S^{+++} + 2e$	
k4	$e + O \rightarrow O^+ + 2e$	
k5	$e + O^+ \rightarrow O^{++} + 2e$	
<b><u>Atom-Ion Reactions</u></b>		
k6	$S + S^+ \rightarrow S^+ + S$	
k7	$S + S^{++} \rightarrow S^{++} + S$	
k8	$S + S^{++} \rightarrow S^+ + S^+$	
k9	$S + S^{+++} \rightarrow S^+ + S^{++}$	
k10	$S + S^{+++} \rightarrow S^{++} + S^+$	
k11	$S + O^+ \rightarrow S^+ + O$	
k12	$S + O^{++} \rightarrow S^+ + O^+$	
k13	$S + O^{++} \rightarrow S^{++} + O^+ + e$	
k14	$O + O^+ \rightarrow O^+ + O$	
k15	$O + O^{++} \rightarrow O^{++} + O$	
k16	$O + O^{++} \rightarrow O^+ + O^+$	
k17	$O + S^+ \rightarrow O^+ + S$	
k18	$O + S^{++} \rightarrow O^+ + S^+$	
k19	$O + S^{+++} \rightarrow O^+ + S^{++}$	
<b><u>Ion-Ion Reactions</u></b>		
k20	$S^+ + O^{++} \rightarrow S^{++} + O^+$	
k21	$S^+ + S^{+++} \rightarrow S^{++} + S^{++}$	
k22	$S^{++} + O^{++} \rightarrow S^{+++} + O^+$	
<b><u>Molecule-Ion Reactions</u></b>		
k23	$SO + S^+ \rightarrow SO^+ + S$	
k24	$SO + S^{++} \rightarrow SO^+ + S^+$	
k25	$SO + S^{+++} \rightarrow SO^+ + S^{++}$	
k26	$SO + O^+ \rightarrow SO^+ + O$	
k27	$SO + O^{++} \rightarrow SO^+ + O^+$	
k28	$SO_2 + S^+ \rightarrow SO_2^+ + S$	
k29	$SO_2 + S^{++} \rightarrow SO_2^+ + S^+$	
k30	$SO_2 + S^{+++} \rightarrow SO_2^+ + S^{++}$	
k31	$SO_2 + O^+ \rightarrow SO_2^+ + O$	
k32	$SO_2 + O^{++} \rightarrow SO_2^+ + O^+$	
<b><u>Recombination Reactions</u></b>		
k33	$e + S^{+++} \rightarrow S^{++} + hv$	
k34	$e + SO^+ \rightarrow S + O$	
k35	$e + SO_2^+ \rightarrow SO + O$	
k36	$e + SO_2^+ \rightarrow S + O_2$	
<b><u>Electron-Molecular Reactions</u></b>		
k37	$e + SO \rightarrow SO^+ + 2e$	
k38	$e + SO \rightarrow S^+ + O + 2e$	
k39	$e + SO \rightarrow S + O^+ + 2e$	
k40	$e + SO^+ \rightarrow S^+ + O + e$	
k41	$e + SO_2 \rightarrow SO_2^+ + 2e$	
k42	$e + SO_2 \rightarrow SO^+ + O + 2e$	
k43	$e + SO_2 \rightarrow S^+ + O_2 + 2e$	
k44	$e + SO_2 \rightarrow SO + O^+ + 2e$	
k45	$e + SO_2 \rightarrow SO^+ + O + e$	

The production and loss contributions in the two-dimensional Io plasma transport calculations for a given ion species can be divided, as introduced by Smyth and Marconi (2003 a, b), into an Inner Region source, originating below Io's exobase, and an Outer Region source, originating above Io's exobase in the gravitational bound satellite corona and its escaping neutral clouds. The Inner Region source is essentially a point source at Io's instantaneous location for which the production source rate in the transport model may be specified. For the Outer Region source, the relevant ion production and loss contributions for neutral-plasma reactions are specified by the calculated volumetric ion production and loss rates as determined by the neutral cloud models for O, S, SO and SO<sub>2</sub> for suitably defined exobase source conditions and the subsequent plasma torus chemistry in Table 2. Efforts in the second quarter have been directed to refining the chemistry rates in Table 2 and to adding as necessary in the Io neutral cloud models for O, S, SO, and SO<sub>2</sub> suitable production and loss output arrays for the ion species.

## References

- Smyth, W.H. and M.L. Marconi (2003a) Nature of the Iogenic Plasma Source in Jupiter's Magnetosphere I. Circumplanetary Distribution, *Icarus*, in press.
- Smyth, W.H. and M.L. Marconi (2003b) Nature of the Iogenic Plasma Source in Jupiter's Magnetosphere II. Near-Io Distribution, *Icarus*, submitted.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE July 25, 2003	3. REPORT TYPE AND DATES COVERED Quarterly, March 19, 2003 to June 18, 2003		
4. TITLE Two-Dimensional Transport Studies for the Composition and Structure of the Io Plasma Torus		5. FUNDING NUMBERS NASW-02003		
6. AUTHORS William H. Smyth				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Atmospheric and Environmental Research, Inc. 131 Hartwell Avenue Lexington, MA 02421		8. PERFORMING ORGANIZATION REPORT NUMBER  P-1037		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) NASA Headquarters Headquarters Contract Division Washington, DC 20546		10. SPONSORING/MONITORING AGENCY REPORT NUMBER  NASW-02036		
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  Research efforts in the second quarterly period have been focused primarily upon reviewing and assessing the neutral-plasma reactions and the plasma-plasma reactions that are important in determining the production and loss rates for the primary heavy ion species $S^+$ , $S^{++}$ , $S^{+++}$ , $O^+$ , and $O^{++}$ in the plasma torus and in acquiring new and updating old cross sections for the important processes.				
14. SUBJECT TERMS  Io plasma torus, plasma structure and transport			15. NUMBER OF PAGES 5	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT  Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE  Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT  Unclassified	20. LIMITATION OF ABSTRACT  Unlimited	